EXPERIMENTAL STUDY OF COMPOSITE-TO-STEEL ADHESIVE JOINTS WITH LASER TREATED SURFACES

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Keywords: adhesive bonding, double strap joint, surface preparation, laser texturing

Abstract

Joining of composite and steel parts is an essential research field, necessitating extensive studies investigating the effect of the many parameters that affect the strength of a composite-to-steel adhesive joint. The present work presents an experimental parametric study of adhesively bonded double strap CFRP/steel joints. Two conventional and two laser texturing surface preparation methods, as well as two different overlap lengths are considered. The experimental measurements are analyzed resulting in important conclusions regarding the failure modes, as well as the effect of the surface preparation method and the overlap length on the strength and stiffness of the joint.

1. Introduction

In general, two kinds of joining methods for similar or dissimilar non-weldable structural materials exist, namely mechanical fastening (bolting, riveting) and adhesive bonding. The traditional mechanical fastening methods are preferred due to the simplicity and the disassembly ability they offer. However, mechanical fastening may cause problems resulting in stress concentrations at the fastener holes, weight increase of the structure and very high bearing stresses in composites. Therefore, adhesive bonding seems to be a very promising method for bringing together structural materials, overcoming the aforementioned obstacles.

Adhesive bonding can be used either as a joining method or for the composite patch repair and rehabilitation of existing metallic structures, using bonded fiber reinforced polymers (FRP) and especially carbon fiber reinforced polymers (CFRP). Application of bonded CFRP materials results in reduced stress concentrations compared to mechanical fastening. Generally, CFRP composites are an excellent candidate for rehabilitation of steel structures, due to their outstanding properties, such as low density and resistance to corrosion. For these reasons, adhesive bonding between CFRP composites and metallic parts has been adopted by several industries in many applications, e.g. aerospace, marine and civil engineering ones, and many researchers are investigating this concept [1-5].

Joining of composite and steel parts is an essential research field, necessitating extensive studies investigating the effect of the many parameters that affect the strength of a composite-to-steel adhesive joint. The present work presents an experimental parametric study of adhesively bonded double strap joints (DSJ) between dissimilar materials, namely between typical marine grade steel and carbon fiber reinforced polymers, where the composite is directly laminated on the steel. The purpose of this study is to investigate the potential of using laser surface texturing as a means for surface preparation of the steel adherents and extract valuable knowledge that will be used in the design of this type of joints for connecting steel and composite structural parts. Four different surface preparation methods and two different overlap lengths are considered and experimentally tested, resulting in a total of 48 tests. The experimental measurements are analyzed, resulting in important qualitative conclusions regarding the damage propagation paths, as well as in important quantitative conclusions regarding the effect of the surface preparation method and of the overlap length on the strength and stiffness of the joint.

2. Experimental program

2.1. Materials

Two different materials have been considered for the fabrication of the adhesive joints, i.e. CFRP and steel. The resin of the composite system was used as the adhesive. The reinforcement material of the composite system involves 322 g/m^2 unidirectional carbon fabrics, supplied by Fibermax composites (www.fibermax.eu). The tensile strength of the carbon fibers is equal to 4900 MPa and their tensile modulus is equal to 240 GPa. The matrix was epoxy resin R9330 with H9554 hardener, both provided again by Fibermax composites. The tensile strength of the epoxy resin is equal to 60 MPa and its tensile modulus is equal to 2.7 GPa. Composite adherents were manufactured with the vacuum bagging method. They were laminated directly on the steel substrates and were cured at 25^o C for 24 hours under a constant pressure of 0.6 bar. Material characterization tests of the produced carbon/epoxy composite resulted in a tensile modulus of 117.4 GPa and a tensile strength of 1187 MPa, for a fibers weight fraction of 59%. The steel adherents were made of common 6 mm thick AH36 steel. The composite straps were approx. 3 mm thick and consisted of 10 layers, resulting in a stiffness ratio of the adhesive joint equal to 0.3.

2.2. Test specimens

Double strap joints were chosen in order to investigate the performance of the CFRP/steel bond. Joints with two different overlap lengths (L_{ov}), namely 50 and 100 mm, were manufactured and experimentally tested. The geometry of the specimens is shown in Fig.1, their width being 50 mm. A length of 50 mm at each edge of the specimens was inserted in the testing machine fixtures. In order to guarantee homogeneity between specimens, large steel plates were used for manufacturing the adhesive joints, from which individual specimens were cut. For the joints with the 50 mm overlap length, two steel plates with dimensions of 500 mm x 200 mm x 6 mm were used, whereas for the joints with the 100 mm overlap length, two steel plates with dimensions of 500 mm x 250 mm x 6 mm were used.

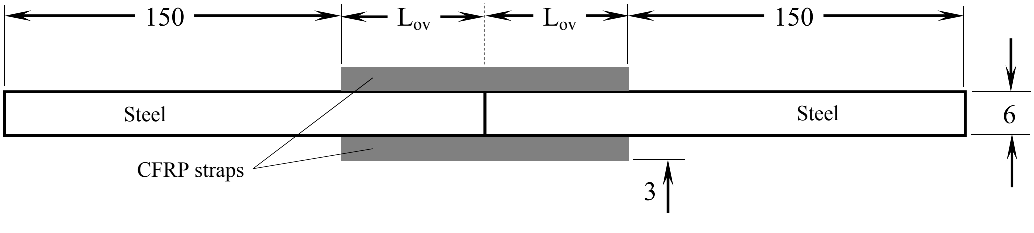
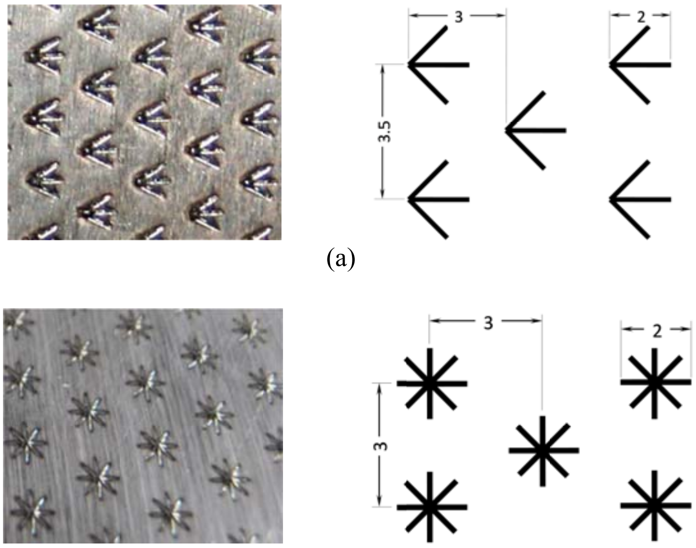


Figure 1. Schematic view and geometry of the joints specimens.



(a)

(b)

Figure 2. The laser made triangle-like (a) and star-like (b) texturing configurations.

Four different methods were examined for the surface preparation of the steel plates. The surface preparation methods involved two different laser surface texturing configurations arranged in regular patterns. These configurations were obtained by melt pool displacement with a high brilliance fibre laser, which allows to produce a spike-hole combined topography in a directional (triangle-like, method A) or in a homogeneous (star-like, method B) arrangement. Laser power up to 400W-CW was focused on a 30 microns spot on the steel and it scanned repeatedly to form the textures by means of a high speed galvoscanner head (up to 1 m/s scanning speed). The final topography is a result of the scanning pattern, the laser parameters (mainly power) and the number of repetitions, which affects the total height. The two different arrangements and the relevant size and spacing of the laser produced patterns are illustrated in Fig. 2. For comparison reasons, an additional set of specimens was made using grit blasting to SA2½ (method S) and another set using a rotating hand-held grinder with 120 grade sandpaper (method H) for the steel surface preparation in the overlap area.

Eight cases were considered in total, that differ in the method of the steel plates surface preparation (A, B, S or H) and in the overlap length (50 or 100 mm), the aim being to evaluate the effect of each one of these parameters on the stiffness and strength of the joint. Therefore, the joints manufactured were A-50, A-100, B-50, B-100, S-50, S-100, H-50 and H-100.

For the fabrication of each joint, the two steel plates were initially aligned in position before applying the CFRP straps. The CFRP layers were then applied on one side of the plate and were cured for 24 h. The same procedure was then repeated on the other side of the plates. After the completion of the curing process, the test specimens were cut out from each one of the parent bonded assemblies with the use of water jet. A milling machine was then used to cut off the CFRP strap edges, so that they have exactly the required length. Finally, six specimens were tested for each joint, resulting in a total of 48 tests. Fig. 3 (left) shows a side view of the CFRP straps cut off edges.

All specimens were loaded by a uniaxial static tensile displacement, applied with a speed of 0.1 mm/min by an MTS hydraulic testing machine. Extensometers were placed on each DSJ specimen in order to monitor longitudinal strain on the CFRP straps. Apart from strains, applied testing machine displacement and reaction forces were also monitored during the

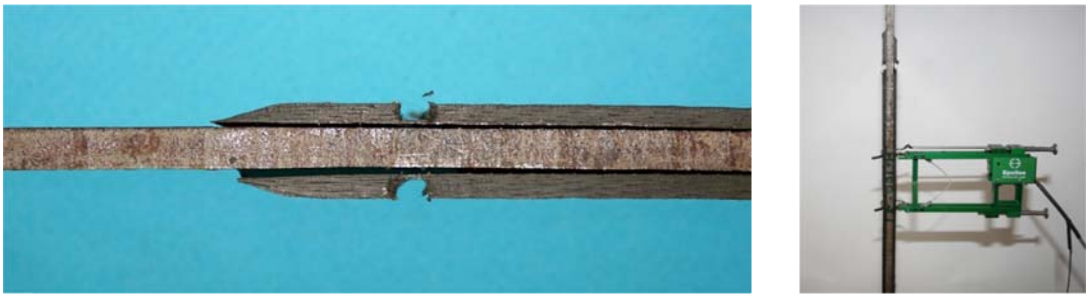


Figure 3. Cut off CFRP strap edge (left) and typical S-100 specimen during testing (right).

tests. Fig. 3 (right) shows a typical S-100 specimen during testing, with the extensometer for the strain measurement attached on it.

3. Experimental results

Fig. 4 is an indicative graph of the relation between the normalized axial displacement (actual displacement over specimen's length) vs. strength for specimens S-50 and S-100, depicting the effect of overlap length on the strength of the joint. This figure shows clearly that the 100 mm overlap length joints are stronger than the 50 mm overlap length ones. Moreover, the nature of the force-displacement curves indicate that the steel adherents of the 100 mm overlap joints are entering plasticity before the final failure, whereas those of the 50 mm overlap joints are not.

The effect of the steel plates surface preparation method is shown in Figures 5 and 6, depicting the strength of some indicative specimens from each group with overlap length equal to 50 and 100 mm, respectively. Both these figures show clearly that the sandblast surface preparation (method S) is exhibiting the best performance, far beyond all the others. Sandblasting is followed by the sandpaper grinding (method H), which in turn is followed by the two laser methods A and B. Fig. 6 for 100 mm overlap length is also showing the entrance into plasticity of the steel adherents of the sandblasted joint before the final failure,

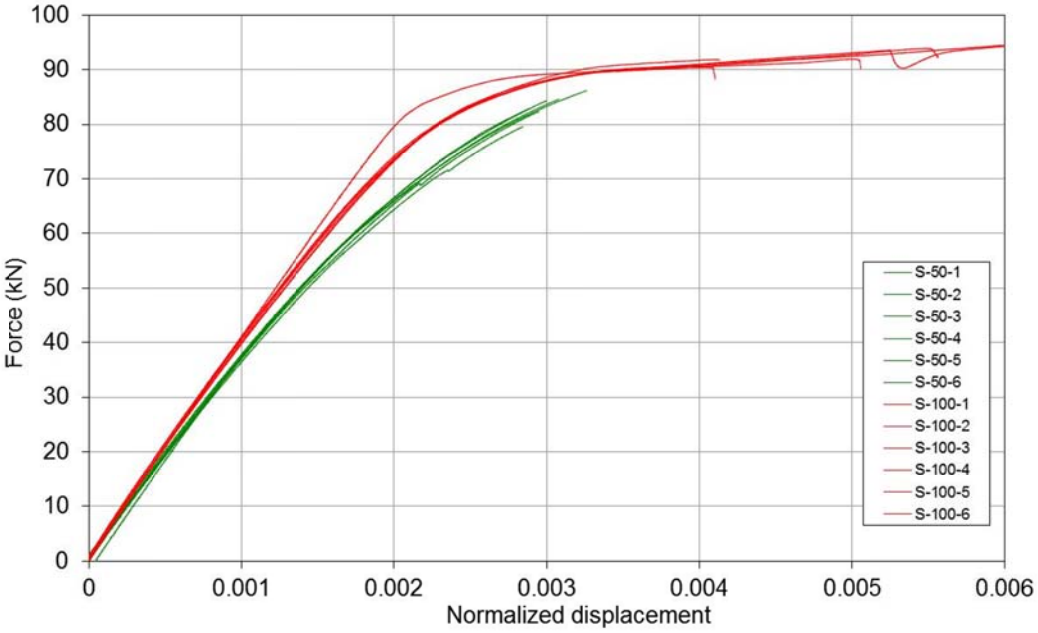


Figure 4. Strength vs. displacement results for the S-50 and S-100 specimens.

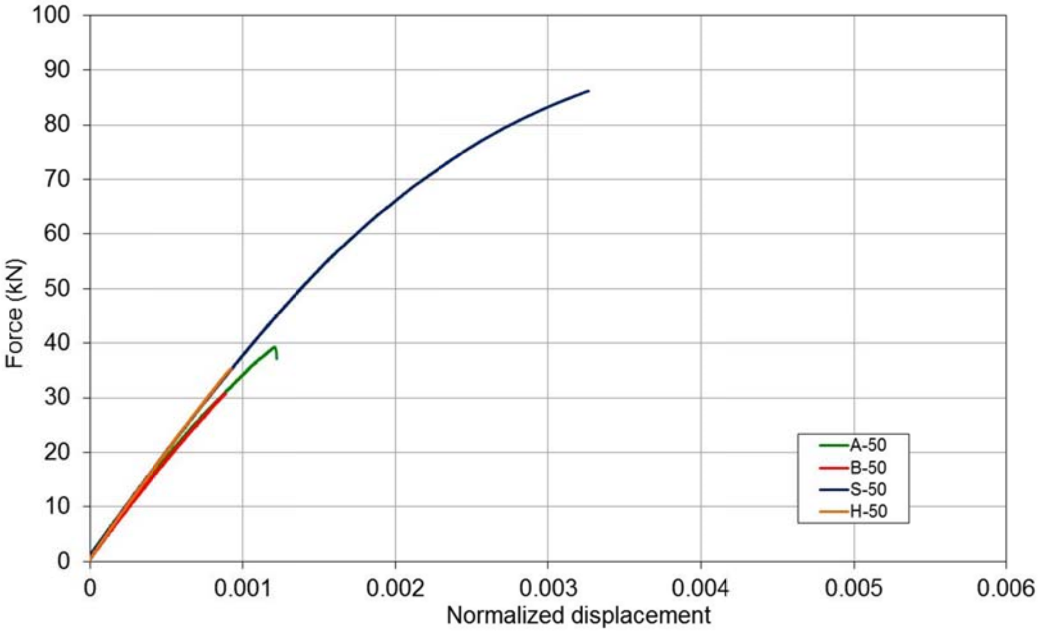


Figure 5. Strength vs. displacement results for 50 mm overlap length specimens, for all surface preparation methods.

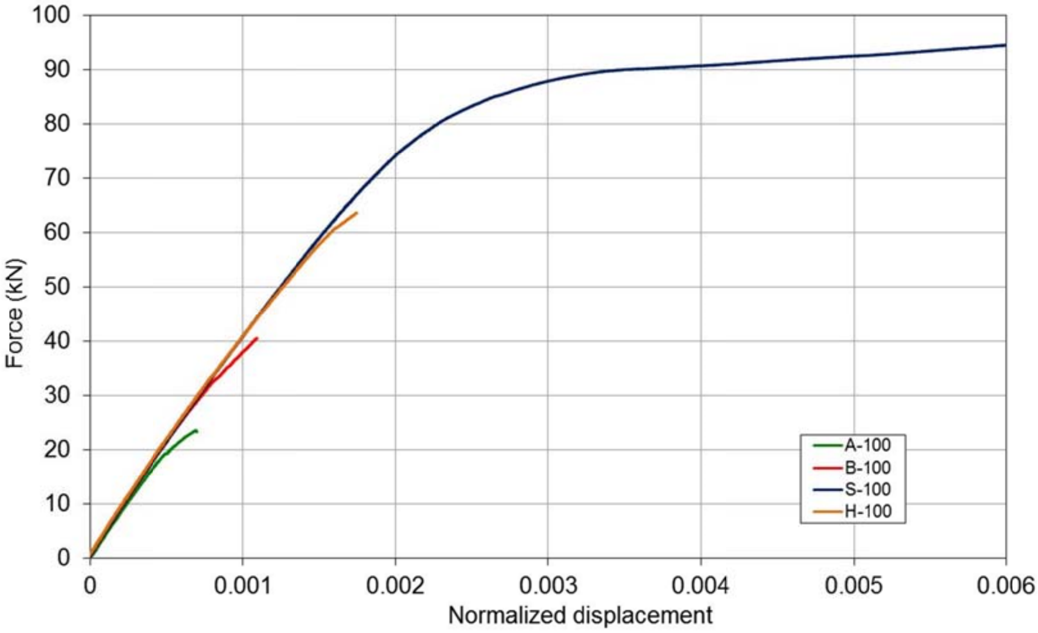


Figure 6. Strength vs. displacement results for 100 mm overlap length specimens, for all surface preparation methods.

whereas joints treated with all other surface preparation methods fail quite earlier without the steel adherents entering plasticity.

An overall view of the test results is presented in Fig. 7 in the form of a bar chart of the average strength values for all eight cases examined (i.e. four surface preparation methods times two overlap lengths). Red colour indicates the 50 mm overlap joints, whereas blue colour indicates the 100 mm overlap ones. The error bars show the percentage coefficient of variation for each group of similar tests. A first conclusion coming out from this graph is that the repeatability of the tests was very good for all surface preparation methods, except for the

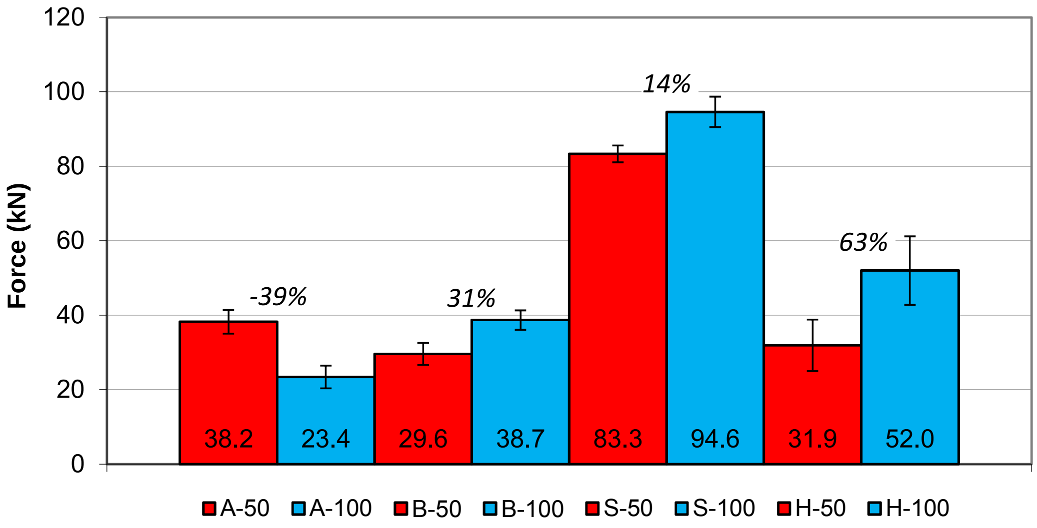


Figure 7. Average joint strength values for all cases examined (values in italics designate differences between the 50 mm and the 100 mm corresponding overlap cases).

method of the sandpaper grinding (H method). This is a strong indication of the inability of this specific surface preparation method to lead to an outcome of constant quality.

Fig. 7 shows also that the 100 mm overlap joints are stronger than the corresponding 50 mm overlap ones, as expected. This is true however only for the B, S and H surface preparation methods, the strength increase varying from 14% to 63% (figures in italics in Fig. 7). In the case of the triangular-like laser surface texturing (method A), a decrease of the strength is noticed for the large overlap length, owing to the significant misalignment of several of the A method specimens tested (see Fig. 8). This misalignment was caused by the non-planar nature of the mother steel plates, developed probably due to their cutting and/or laser surface treatment.

Comparing the surface preparation methods, the superiority of the sandblasted joints is evident from Fig. 7, their load carrying capacities being approximately double those of the other surface preparation methods, regardless of the overlap length. This is probably attributed to the fact that sandblasted surfaces exhibit high and uniform roughness values (average Ra equals to 10.4 μm), contrary to the other methods examined here. More specifically, sandpaper grinding resulted in an average Ra roughness value of approx. 2.0 μm, whereas roughness measurements were not possible for the laser treated surfaces, which however, exhibit very low roughness in-between texturing (no surface treatment at these areas). As regards methods other than sandblasting, a different influence on the strength of the surface preparation method for the two different overlap lengths can be noticed. In order to compare the two laser methods A and B, we should compare only A-50 and B-50 specimens, since A-100 specimens were largely misaligned as mentioned before, thus being not appropriate for comparison purposes. Therefore, it can be concluded that triangular-like laser texturing (method A) results in higher strength values in comparison to the star-like laser texturing (method B). On the other hand, sandpaper grinding (method H) results in satisfactory strength values for the 100 mm overlap length, with a big difference in comparison to the H-50 specimens. This is probably attributed to the significant inhomogeneity in roughness of the corresponding steel surfaces.

An overview of the average measured joint stiffnesses is given in Fig. 9, where again error bars show the percentage coefficient of variation for each group of similar tests. Average

Figure 8. Misalignment of A-100 specimens.

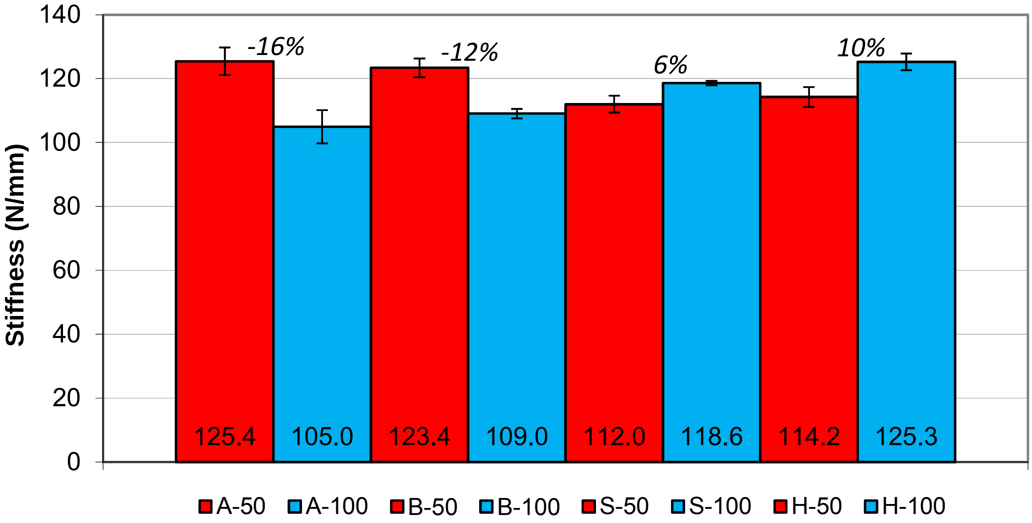


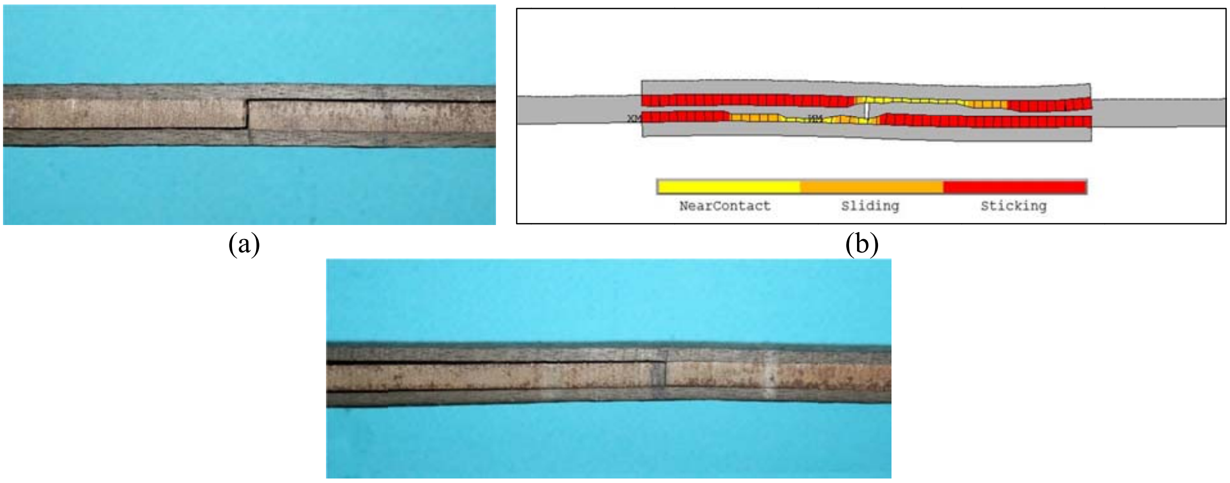
Figure 9. Average joint stiffness values for all cases examined (values in italics designate differences between the 50 mm and the 100 mm corresponding overlap cases)

stiffnesses were derived from the values of the inclination of the corresponding force-displacement curves at their initial linear part. As it is evident from this figure, repeatability of measurements is again very good, whereas average stiffness values present a mixed behaviour, though not presenting significant differences between each other, either with respect to the overlap length or with respect to the surface preparation method.

As regards measured strains on the CFRP straps, they were in general low, reaching maximum values of approximately 2200 microstrains in the case of the S-100 specimens, at their yield load. Repeatability of measurements was in general not good, since the unavoidable small misalignments existing in almost all specimens had a crucial effect on the value of the monitored strains.

4. Failure modes

All specimens failed by adhesive debonding at the interface between the CFRP straps and the steel, the only difference being that plasticity of the steel adherents appeared before debonding in S-100 specimens. In most of the cases the pattern of CFRP straps/steel debonding was antisymmetric, as shown in Fig. 10-a, a mode also predicted by corresponding finite element analyses (see Fig. 10-b, where yellow colour indicates debonding and red colour indicates perfect bond). In some cases however adhesive debonding took place at the two interfaces of the same steel adherent, as shown in Fig. 10-c.



(a) (b)

(c)

Figure 10. Antisymmetric (a-actual, b-FE prediction) and one-sided (c) failure modes of the joints specimens.

5. Conclusions

Eight different CFRP/steel double strap joint cases were experimentally tested in order to investigate the influence of the overlap length and the surface preparation method on the joints' strength and stiffness. Surface preparation involved two conventional methods (sandblasting and sandpaper grinding) and two new laser treatment candidates. As expected, there was a significant effect of the overlap length on the joints' strength. Doubling the overlap length resulted in a significant increase of the joints' strength. In addition, there was a significant effect of the surface preparation method of the steel plates on the joints' strength. Sandblasted surfaces resulted in the highest strength values and star-like laser texturing in the smallest. Repeatability of results was in general very good, except the method of the sandpaper grinded specimens which did not exhibit a constant surface quality. Regarding joints' stiffness, neither the overlap length nor the surface preparation method appeared to have a significant influence.

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